

Improved Temperature Characteristics in Quantum Dot Lasers with Indirect-Bandgap Barriers

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Abstract: This study demonstrates that a much higher characteristic-temperature can be achieved with quantum dot lasers of indirect barrier compared to those of direct barrier. The temperature dependence of threshold current is reduced because the injected carriers residing in the barrier at “high” temperatures recombine slowly.

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OCIS codes: (140.3380) Laser materials; (140.5960) Semiconductor lasers

The driving force behind the quantum dot (QD) studies was the possibility of reducing the laser threshold since the density of states in QDs is ideally much narrower than the density of states in bulk and quantum-well semiconductors. Although the progress in QD Lasers has been significant, they still have not fulfilled their promise because present QD lasers still exhibit strong exponential dependence of their threshold upon temperature due to carrier recombination in the barrier layers that “clad” the dots [1]. In this paper, we propose a new type of QD laser in which the direct-gap QDs are embedded in a semiconductor “matrix” material that has an indirect bandgap. We show that this technique reduces the dependence of threshold current on temperature. Specifically, we have studied InAs QDs in indirect $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers with $x = 0.4$. The choice of $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ barrier material with a lattice parameter almost equal to that of GaAs is made in anticipation of investigating similar InAs QDs in both GaAs and AlGaAs. Thereby, we can establish a fair comparison between QD lasers with direct GaAs barriers and those with indirect $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ barriers. In this paper, a significant reduction in temperature dependence (a much higher “characteristic temperature”) is predicted for the QD lasers with indirect barriers. The reason is that a majority of the carriers reside in the barrier at higher temperatures. The longer effective carrier lifetime due to the indirect nature of the bandgap reduces the demand on the pumping current for maintaining those carriers in the barrier, a region that serves as a reservoir for carrier population in QDs.

The population dynamics is modeled with the theory of random population [2] based on the idea that carrier capture by the dots and recombination in the dots are essentially random processes. We further expand this theory to include the escape process that allows carriers to be thermally released from dots to their surrounding barrier before being recombined [3].

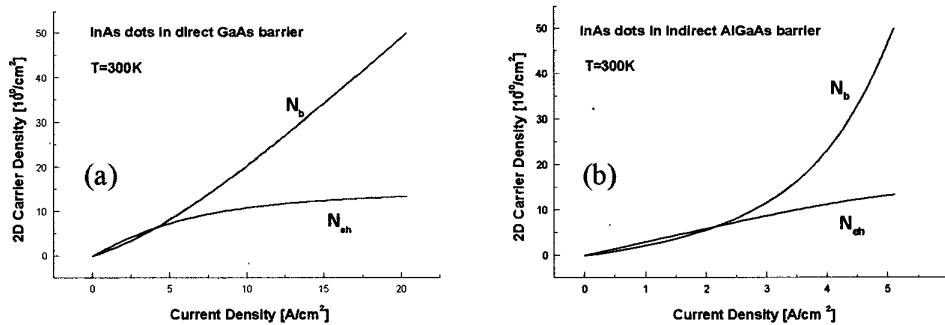


Fig.1 Population distribution at 300K between dots N_{ch} and barrier N_b for InAs dots in barriers of (a) direct GaAs and (b) indirect AlGaAs.

Figure 1 shows the carrier distribution between the dots N_{eh} and barrier N_b as a function of the pumping current density at $T=300K$ for dots with an area density of $4 \times 10^{10} \text{cm}^{-2}$ embedded in either direct or indirect barriers. It can be seen from Figs.1(a) and 1(b) that carriers already starts to accumulate in the barrier before the dots are saturated. In order to maintain a steady-state distribution of carriers in the dots that is sufficient for threshold optical gain, it is necessary to maintain a certain level of carrier density in the barrier. As demonstrated in Fig. 1, the barrier of indirect bandgap requires less pumping current density to inject a given density of carriers.

Based on the analysis of population distribution, we have calculated the optical gain for the ground-state radiative transitions with the assumption that for a typical QD ensemble, the inhomogeneous broadening of the transition linewidth induced by the dot-size variation is much larger than the homogeneous broadening.

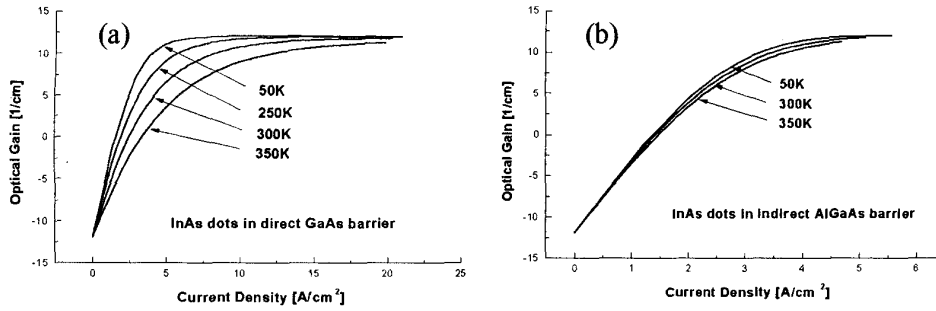


Fig.2 Optical gain as a function of pumping current density at various temperatures for InAs dots in barriers of (a) direct GaAs and (b) indirect AlGaAs.

The result of optical gain at the average transition photon energy is shown in Fig.2. The gain is calculated as a function of pumping current density for QDs with direct (Fig.2a) and indirect barriers (Fig.2b) for several temperatures ranging from 50K to 350K. It can be seen from Fig.2 that the optical gain increases with the pumping current density and reaches saturation value at approximately 12/cm. QD lasers with indirect barriers require less pumping current compared to those with direct barriers to reach the same level of optical gain. Comparing Figs.2(a) and 2(b), optical gain as a function of pumping current for QD lasers with indirect barriers shows rather insignificant temperature dependence, while that of direct barriers clearly indicates a strong temperature dependence. This conclusion is better illustrated with the assumption of a fixed value of optical gain that is required to compensate the typical losses ($2 \sim 10/\text{cm}$) found within QD laser cavities. Taking the value of threshold gain as $g_{th}=8/\text{cm}$, we have calculated the threshold current density J_{th} as a function of temperature. The result is shown in Fig.3 for QD lasers with direct and indirect barriers. Fig.3 reveals that QD lasers with indirect barriers require less pumping to reach J_{th} throughout the temperature range, and that J_{th} remains almost unchanged as the temperature increases. For QD lasers with direct barriers, even though their J_{th} can be low at “low” temperatures, J_{th} increases sharply as the temperature increases. The rather significant difference in J_{th} between the two cases at higher temperature is the direct result of the lifetime difference between the two types of barriers where there is an inevitable carrier buildup at elevated temperature. We have fitted our data to the standard threshold-temperature expression: $J_{th}=J_0 \exp(T/T_0)$ where T_0 is the characteristic temperature of the laser. For the temperature range of $50 \sim 350K$, we obtain $T_0=305K$ for the direct barrier and $T_0=2857K$ for the indirect barrier. For the higher temperature range of $260 \sim 350K$, we obtain $T_0=153K$ for the direct barrier and $T_0=1152K$ for the indirect barrier, an enormous improvement. The T_0 value that we obtained for QDs in direct barrier at higher temperature is consistent with the 161K value measured over the same temperature range in the InAs QD laser with GaAs barrier [4].

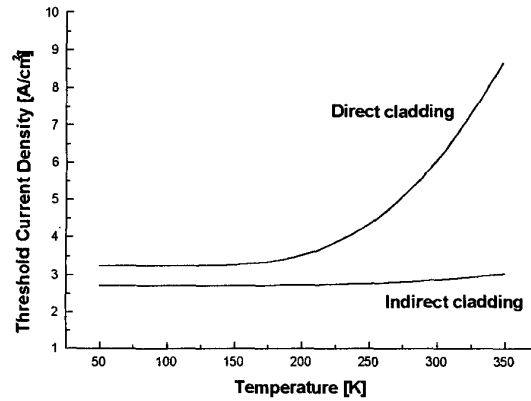


Fig.3 Pumping threshold current density as a function of temperature to maintain optical gain of 8/cm for InAs dots in direct and indirect AlGaAs barriers.

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